THE PHOSPHORUS NUTRITION OF SEEDLINGS IN RELATION TO PHOSPHATE FIXATION BY TWO HAWAIIAN SOILS

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INTRODUCTION

Phosphorus nutrition of plants is particularly important during the early stages of growth. Since the root system of seedlings is limited in extent, the developing embryo must depend greatly on seed reserves of phosphorus. Perhaps it is because of this that seeds generally contain more phosphorus than do other plant parts. Fox and Albrecht (1957) showed that wheat grain, especially the embryo, is rich in phosphorus. Values as high as 18,000 ppm. have been reported. If the internal phosphorus supply is depleted as a result of external factors, growth may be retarded and the chance of survival decreased. It is even possible as Gericke (1924) showed, using wheat plants, that damage done by phosphorus starvation during the early seedling stage can not be rectified later by a good supply.

Visual observations made during previous studies with seedlings seemed to show that phosphorus deficiency developed in the first true leaves and even in the cotyledons of dicots growing on phosphate-deficient Hawaiian soils. The work of De Datta (1963) revealed an interesting aspect of this problem. He reported that phosphorus concentration and phosphorus yield in Sudan grass (*Sorghum vulgare* var. *sudanense*) grown entirely in vermiculite culture were higher than in plants grown first in vermiculite and then placed in contact with the soils lacking in fertilizer phosphorus. The studies conducted by Emmert (1949) on the loss of phosphorus-32 by plant roots after foliar application suggest that while root loss of phosphorus-32 is considered exclusively a root phenomenon, such loss may indeed involve forces residing outside of the root. If the loss of phosphorus from plants is related to the phosphate status of the medium, it is appropriate to investigate the relationship between phosphorus fixation by the soil and loss of phosphorus from the plant.

It was demonstrated that the full phosphorus requirements of some plants could be satisfied during the first four weeks of growth (Gericke, 1924). The amount of phosphorus available in the soil solution for plant absorption is usually very small. Burd and Martin (1923), and Pierre and Parker (1927) showed that concentrations of phosphorus in soil solution or water extracts of soil are of the same order of magnitude and ordinarily much less than 1 ppm. In some cases, phosphorus fertilization of deficient soils has not effectively provided for plant phosphorus needs. And many investigators attribute this low fertilizer phosphate recovery to the fixation or immobilization of phosphorus in the soil. Thus, according to Gilbert (1948), in order to obtain optimum yields of most crops, a much larger amount of phosphorus fertilizer must be applied than what is actually needed by the crop because some of the phosphorus becomes immobilized in the soil and is not immediately available for absorption.

Low fertilizer phosphate recovery by crops is a serious problem in many Hawaiian soils. It was shown by Chu and Sherman (1952) that as much as 90% of added soluble phosphate is fixed in the presence of iron and aluminum oxides between pH 3.0 and pH 4.0. Fox et al. (1962) studied phosphate fixation by seven Hawaiian soils, representing six great soil groups. According to them, the order of fixation is as follows: Amorphous hydrated oxides > goethite - gibbsite > kaolinite or 1 : 1 clays > montmorillonite or 2 : 1 clays. Since the seedling stage is critical in the development of a plant and since observation has indicated that phosphorus deficiency may develop concurrently with germination, a study of some factors influencing phosphorus nutrition of seedlings was considered very worthwhile.

The objectives of the studies conducted and reported in this paper are as follows:

1. to determine possible loss of phosphorus from seedling roots in relation to phosphorus status in soils, and

2. to determine uptake of applied fertilizer phosphorus as influenced by time, rates, methods of application, and phosphate fixation in soils.

REVIEW OF LITERATURE

Movement of phosphate ion.

The movement of phosphate ion in the plant is rather rapid. Using a radioactive phosphorus as an indicator, Arnon *et al.* (1940) observed that after 40 minutes, newly-absorbed phosphorus was detected in the leaves and tips of tomato plants over 6 feet tall. The movement of phosphorus from plant roots to a medium had been studied by several investigators. Brewer (1940) observed that the phosphorus content of corn leaf seedlings decreased only slightly with time and the phosphorus concentration of the medium increased slowly through the loss of phosphorus from the roots and lower portion of the stalk. According to Fedorovskii (1958), phosphorus loss from corn was 4 to 25% of the original plant phosphorus. The work of Jenny *et al.* (1939) showed that intake of ions in plant was not a uni-directional process; ions of some species might move into the root and out of the root at the same time. The outgo was especially pronounced when the roots were in contact with the colloidal system. The significance of this phenomenon as pointed out by Emmert (1949) was that loss of ions by roots might play an important role in the overall nutrient economy of the plant since such loss was of such considerable magnitude as to be detected chemically in plant growth medium and to cause significant reduction in the nutrient content of plant tops.

The movement of phosphate ion in the soil is very slow. Sell and Olson (1947) reported that there was no detectable movement below 1 inch in a sandy loam soil during a period of 3 years when 80 pounds P_2O_5 as superphosphate was applied as top dressing. This indicates the importance of applying phosphate fertilizer so that plant roots will intercept fertilized soil at the appropriate time to supply plant phosphorus need.

Factors affecting effective phosphorus fertilization.

There are four important factors which greatly influence the effectiveness of phosphorus fertilization. According to Stanford and Pierre (1953), the factors of time, rate, frequency and method of application all influence phosphorus availability in soils largely by affecting the degree and rate of fixation of applied phosphorus. They point out that these factors are closely related in practice so that it is often difficult to evaluate their separate effects; besides, there is the possibility of one of these factors greatly affecting the importance of another.

Uptake relationship of fertilizer phosphorus (P^{31}) and phosphorus isotope (P^{31} and P^{32}) in fertilizer.

It has been shown by some workers that stable phosphorus (P^{31}) and radioactive phosphorus (P^{32}) are absorbed by the plant in the same magnitude and that these two isotopes perform the same function in the plants. The difference between the two is their atomic weights. According to Boulden and Black (1960) and Mattingly and Talibuden (1961), the high sensitivity of an isotope is a major advantage when used to evaluate fertilizer uptake by plants. It provides a means of detecting differences in nutrient availability under conditions when nutrient uptake is too low to be estimated by chemical methods.

Phosphorus fixation and availability

Much work has been done on phosphorus fixation in soils. For the purpose of this paper, it is sufficient to define fixation as interpreted by Dean and Kardos. Dean (1949) defined fixed phosphorus as soil phosphorus which has become attached to the solid phase of soils. Kardos (1955) interpreted the fixation phenomenon as the processes whereby readily soluble plant nutrients are changed to less soluble forms by reaction with inorganic components of soils with the result that the nutrients become restricted in their mobility in the soil and suffer a decrease in their availability to plants.

Mechanism of phosphorus fixation and factors affecting it.

According to Russell (1961), there are only two important mechanisms by which soils fix phosphate in the field, namely, those involving iron and aluminum ions. There is a possibility of a third process, that of phosphate being held on the edges of the clay particles through hydrogen bonding between the hydroxyls in the broken edges.

Several investigators have investigated the course and extent of reactions by which added soluble phosphates fixed in the soils may be influenced by different factors. Some of the factors are:

1. Concentration of phosphate ions in soil solution. Fixation is a function of the concentration in the solution at equilibrium (Hibbard, 1935).

2. Time of reaction. Some of the surface reactions (adsorption in the ion atmosphere, counter ion adsorption, and possible exchanges of some types of surface hydroxls) are completed quickly and the rate of reaction decreases rapidly (Kurtz, 1953).

3. Temperature. The rate of absorption is increased by increased temperature, but it is believed that the nature of the reaction is unchanged (Low and Black, 1950).

4. Reaction (pH) of the solution. Maximum adsorption is at low pH levels 3.0 to pH 4.0 (Kurtz, 1953).

5. Type of mineral. Kaolinite has a large capacity to take up phosphate because of an exchange of phosphate with the layers of hydroxyl ions on the surface of the mineral (Stout, 1939).

6. Particle size. Phosphate adsorption increases with decreasing particle size and finer clay fraction has appreciably greater anion-adsorption capacities than coarser fractions (Colman, 1944).

7. Exchangeable cations. Even at pH levels below neutrality, where calcium precipitation would not be expected, calcium clays retain more phosphate than do sodium, ammonium, or potassium clays (Heck, 1934).

8. Effect of salts. In general, phosphate adsorption increases in the presence of electrolytes in the solution (Kurtz et al., 1946).

MATERIAL AND METHODS

Soils (media) studied.

Two surface soils, each representing a great soil group, were used in this study. Their chemical characteristics are shown in Table I.

Lualualei soil. The Lualualei soil series belongs to the Dark Magnesium Clay great soil group, resembling the "Regur" or "Black Cotton Soils" of India and the "Black Earths" of Australia in their physical and chemical characteristics (De Datta, 1963). Soils of this series are derived from alluvial parent material and are found at an elevation of less than 250 feet in an area which receive an annual rainfall of 15 to 25 inches. The dominant clay minerals are montmorillonite (2:1 clays). A representative sample of this soil was collected for this study from the Lualualei Valley in the Waianae area of the island of Oahu.

Kapaa soil. The soil from the Kapaa series is very deep, with a well drained Aluminous Ferruginous Latosol developed in saprolitic ferruginous bauxite found on the gently sloping uplands of the island of Kauai. The elevation of the soil area is between 200 and 1000 feet, with an average annual rainfall of 60 to 100 inches.

The magnitude of phosphate fixation in Lualualei and Kapaa soils as affected by phosphate concentration and various time of phosphate solution - soil contact were studied by Yaptenco et al. (1963). They showed that after 12 days of phoshate solution - soil contact, Lualualei soil fixed 96% and 46% while Kapaa soil fixed almost 100% and 93% of the phosphate added at 5 ppm. and 500 ppm., respectively (Table II).

Table I. Chemical characteristics of two Hawaiian soils belonging to two great soils groups (De Datta, 1963)

Property Measured	Soil Series	
	Lualualei	Kapaa
pH (H_20)	7.8	4.8
pH (KCl)	6.9	4.4
Phosphorus in water extract (ppm.)	3.82	0.02
H_2SO_4 - extractable soil P (ppm.)*	966.2	3.7
Extractable ($BaCl_2$) aluminum (m.e./100g. soil)*	0.01	3.28
Extractable (NH_40Ac-$BaCl_2$) aluminum (m.e./100g. soil)*	0.07	10.40
Aluminum in water extract (ppm.)	0.09	0.06
Cation exchange capacity (m.e./100g. soil)	42	29

*Values are expressed on oven-dry soil basis

Experiment I. The loss of phosphorus from seedling roots in relation to phosphate fixation in soils.

The possible loss of phosphorus from seedling roots was studied using four plant species and three plant growth media. Two methods of approach were adopted for this phase of the study.

Experimental design. A 2 by 3 (plants and media, respectively) factorial experiment in randomized block design was adopted. The treatments were replicated 3 times and conducted in two sets; one was assigned for harvesting 7 days after seeding, and the other 16 days after seeding.

Greenhouse procedures. Two greenhouse techniques were employed.

a. Direct seeding. Using 12-ounce capacity, round, waxed carton containers, 200 gm. sample of previously prepared air-dried Lualualei and Kapaa soils and 250 gm. washed quartz sand were potted. Into these media, the indicator plants, soybean (*Glycine max*) and alfalfa (*Medicago sativa*), were directly seeded at the rate of 12 and 150 seeds per container, respectively. Blanket application of nutrient solution (80 ppm. nitrogen and 225 ppm. potassium as potassium nitrate, soil basis) was added to all pots. Moisture was also applied uniformly in all treatments. Upon germination, the soybean plants were thinned to 10 per pot while the alfalfa plants were thinned to 130 per pot. The plants were sampled from one set of treatments at the age of 7 days and from another set at the age of 16 days, separating the tops, cotyledons, and roots.

b. Root pad-soil contact. The method employed was adopted from the technique described by Stanford and De Ment (1953) which consisted of preparing round waxed cartons (12-ounce capacity) with bottoms removed and nested in identical containers with bottom intact. The containers were filled with 700 gm. of washed quartz sand. The test plants, which consisted of corn (*Zea mays*) and Sudan grass (*Sorghum vulgare* var. *sudanense*), were then seeded in the medium at the rate of 8 seeds per pot and 30 seeds per pot, respectively. Two weeks after planting, the corn plants were thinned to 5 plants per pot while the Sudan grass plants were thinned to 20 plants per pot. Moisture and nutrient solution other than phosphorus were supplied uniformly to all pots. From the second to the third week period, a thick dense root pads formed at the bottom of the container. During this time, plants also began to show symptoms of phosphorus deficiency.

At the end of 3 weeks, the sand carton containing plants were then nested in a second set of cartons of the same size which contained 400-gram samples of either Kapaa or Lualualei soil so that root pads were in contact with the soil. One set of the sand carton containing plants was also nested in a second set of cartons which contained 250-gram sand. The plants were kept in contact with the soils for 5 days after which the plants were harvested, separating the tops from the roots.

Preparation of plant samples. All the harvested plant samples were dried in the oven at 80°C and weighed. The plant samples were then ground in a Wiley Mill, except for the alfalfa samples which were relatively small and were processed intact.

Chemical analyses. All of the alfalfa plant samples and 150 mg. of each of the other plant materials were ignited with alcoholic magnesium nitrate in silica crucibles and ashed for 12 to 14 hours in a muffle furnace at 600°C. The plant ash samples were dissolved in 10 ml.

of 1N HCl, and total phosphorus was determined colorimetrically as molybdivanadosphosphoric acid as described by Kitson and Mellon (1944).

Experiment II. The uptake of applied fertilizer phosphorus as influenced by time, rates, methods of application, and phosphate fixation in soils.

The influence of time, rates and methods of phosphorus fertilization and phosphate fixation in two soils on the uptake of fertilizer phosphorus by seedlings was studied.

Experimental design. A 3 by 2 by 3 (rates, methods, and time of growth, respectively) factorial in randomized block design was adopted in the study of this problem. The treatments were replicated 3 times.

Greenhouse procedures. 1300 gm. of the air-dried samples of Lualualei and Kapaa soils were potted in 46-ounce capacity tall metal juice cans lined with polyethylene bags. This amount of soil made up a volume of about 1 inch from the top when contained in the metal cans.

Corn (Zea mays) was used as the indicator plant. Corn seeds were soaked for 12 hours prior to seeding in pots at the rate of 15 seeds per pot. Upon germination, plants were thinned to 12 per pot.

Two phosphorus solutions were prepared from standardized stock phosphoric acid. The final solution was then tagged with P^{32}. The P^{32} labeled phosphorus solutions were prepared in such a way that a 25 ml. sample applied per pot gave either 25 ppm. P or 300 ppm. P on a soil basis. These rates were approximately 50 pounds per acre and 600 pounds per acre, respectively.

Two methods were used for applying the phosphorus solution in the potted soils. By one method, the phosphate solution was thoroughly mixed with the soil material in a shell blender. The second method was done as follows: After the proper amount of soil was added to each pot, two aliquots of soil, 150 ml. and 250 ml. were removed from each pot. The soil surface in the pot was then leveled. The phosphate solution was mixed with the 150 ml. aliquot and the mixture was placed back as a uniform layer in the pot. The corn seeds were placed on the surface of the phosphate fertilized layer. Finally, the second 250 ml. aliquot of soil was used to cover the seeds. The minimum depth of the phosphate fertilizer layer was about 1 inch from the soil surface.

A blanket application of nutrient solution (80 ppm. nitrogen and 225 ppm. potassium as potassium nitrate, soil basis) was applied to all pots. Moisture was controlled in all pots throughout the experiment by periodic weighing of water into the pots.

Chemical and radio-chemical analyses. Two hundred mg. of plant material was ignited with alcoholic magnesium nitrate in silica crucibles and ashed for 12 to 14 hours in the muffle furnace at 600 °C. The plant ash was taken up with 10 ml. of 1N HCl. Total phosphorus was determined colorimetrically as molydivanadophosphoric acid as described by Kitson and Mellon (1944). Plant phosphorus derived from fertilizer was determined by end window β counting of aliquots of evaporated plant digest.

Calculations. From information on total phosphorus (colorimetric method) and radioactivity of the plant material, the P derived from fertilizer and fraction of plant phosphorus derived from fertilizer were calculated as follows:

1. $$\frac{\text{CPM of unknown plant digest (corrected for background)}}{\text{CPM of standard solution (corrected for background)}} \times \text{P in standard solution (ppm.)} \times \text{Dilution factor}$$

= Fertilizer phosphorus in the plant (ppm.)

2. Fertilizer phosphorus in plant (ppm.) X dry matter yield/pot (gm.) = Fertilizer phosphorus yield/pot (mcgm.)

3. Fraction of plant P derived from fertilizer =

$$\frac{\text{Fertilizer P in plant}}{\text{Total P in plant}}$$

RESULTS AND DISCUSSION

Experiment I. The loss of phosphorus from seedling roots in relation to phosphate fixation in soils.

Two techniques, direct seeding and root pad-soil contact, were employed to investigate possible losses of phosphorus from seedling roots in relation to phosphate fixation in Lualualei and Kapaa soils. Seedlings which had been grown from the beginning in soil (direct seeding) were harvested 7 or 16 days after planting. Alfalfa and soybeans were used as indicator plants. Phosphorus contents of tops, roots and cotyledons were determined separately. When root pad-soil contact technique was used, plants were harvested after 5 days of root-soil contact. Sudan grass and corn were used as indicator plants. Phosphorus contents of tops and roots were determined separately.

Direct Seeding Experiment. Yields of alfalfa roots, tops and cotyledons harvested 7 days after planting were greatest in Lualualei soil, intermediate in sand and lowest in Kapaa soil, as shown in Figure 1. Of the three plant parts, the biggest differences among yields of alfalfa grown on the three media were the differences among the roots. These differences were particularly evident after 16 days of growth (Table 3). The data suggest that with time, the root of alfalfa is most drastically influenced by the phosphorus status of the medium.

Root of soybean seedlings, however, responded differently in the sense that relative differences among yields of roots grown in the three media became smaller with time. There was not much difference between the growth of soybean roots in Kapaa soil and sand 16 days after planting (Figure 2).

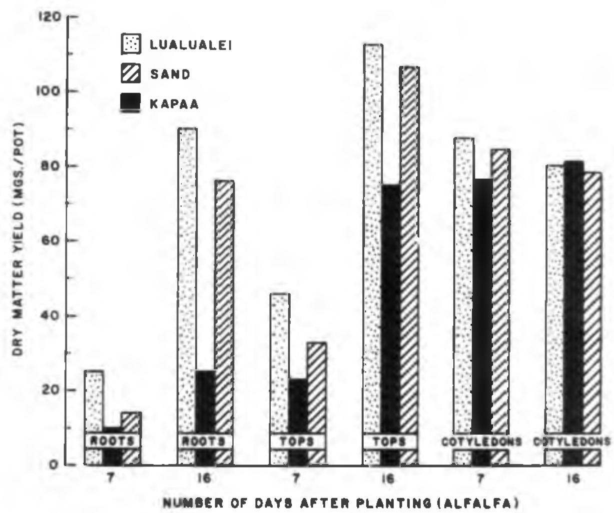

Figure 1. Comparative yield of roots, tops, and cotyledons of alfalfa seedlings harvested 7 days and 16 days after direct seeding.

Table III. Yields (mg./pot) of alfalfa and soybean seedlings 7 days and 16 days after direct seeding 1/

Soil Series	7 days after seeding				16 days after seeding			
	Root	Top	Cotyledon	Whole Plant	Root	Top	Cotyledon	Whole Plant
				Alfalfa 2/				
Lualualei	25	46	88	159	90	113	81	284
Kapaa	10	23	77	111	25	75	82	182
Sand (no soil)	14	33	85	134	76	107	79	262
				Soybean				
Lualualei	256	334	1390	1980	535	1252	704	2491
Kapaa	172	158	1440	1770	459	635	937	2031
Sand (no soil)	203	184	1602	1989	467	515	817	1799

1/ Mean of 3 replications

2/ Although plants were thinned to uniform population soon after germination, the number of plants per pot varied from 98 to 112 at harvest time. Therefore, yields were adjusted to 100 plants per pot.

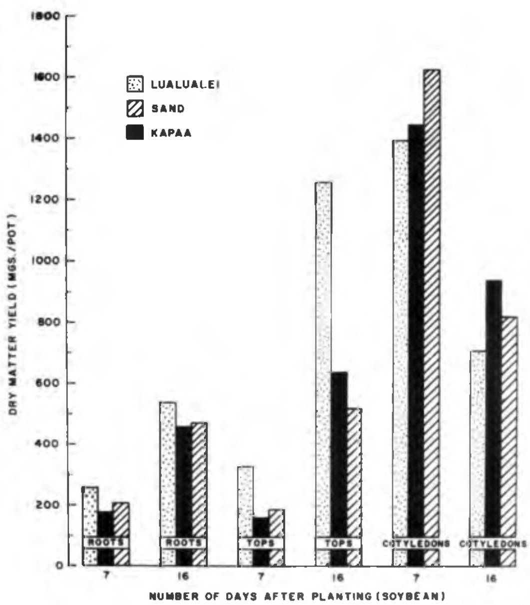

Figure 2. Comparative yields of roots, tops, and cotyledons of soybean seedlings harvested 7 days and 16 days after direct seeding.

This may indicate that the concentration of aluminum in Kapaa soil was not toxic to the soybean root.

Root and top yields of alfalfa, harvested 16 days after planting, gave similar trends as those of the 7-day harvest. In terms of whole plant yields, relative differences between plants grown in Kapaa soil and sand stayed about the same with time.

Soybeans behaved very differently from alfalfa. Whereas yields of plants grown on sand and Lualualei soil were almost identical, the yields in Kapaa soil were greater than those grown in sand, 16 days after planting (Table 3).

The differences in response between alfalfa and soybean seedlings may be related to differential accumulation of aluminum. Alfalfa plants may have accumulated much greater amounts of aluminum than soybean plants. It is also possible that what little amount was taken up by the soybean plants was beneficial.

Phosphorus concentrations and phosphorus yields of alfalfa roots were consistently greatest in plants grown on Kapaa soil, intermediate in sand and lowest in Lualualei soil. This was true 7 days and 16 days after planting (Tables IV and V) and suggests that phosphorus accumulation in the roots is associated with the aluminum and/or iron status of the rooting medium. However, other factors are probably involved. Perhaps one very important factor is the phosphorus requirement of the true leaves. Top growth of alfalfa was least when plants grew on Kapaa soil, 7 days after planting (Figure 1). Yet on the whole plant basis, material of the 7-day harvest contained a higher concentration of phosphorus than similar plant material produced on Lualualei soil and sand.

Table IV. Phosphorus concentration (ppm.) of alfalfa and soybean seedlings 7 days and 16 days after direct seeding. 1/

Soil	7 days after seeding				16 days after seeding			
Series	Root	Top	Coty-ledon	Whole Plant 2/	Root	Top	Coty-ledon	Whole Plant
				Alfalfa				
Lualualei	11600	10800	7940	9250	2750	6190	4880	4720
Kapaa	44200	11900	11600	14810	24450	4910	5470	7810
Sand (no soil)	19810	15000	8260	11530	6520	6000	5090	5880
				Soybean				
Lualualei	7050	8420	8770	8490	6350	6140	9360	7100
Kapaa	8690	7500	8020	8040	7030	6840	7690	7400
Sand (no soil)	7170	8350	8390	8250	6670	7350	7530	7260

1/ Mean of 3 replications

2/ Phosphorus concentration of whole plant ppm. =

$$\frac{\text{Total P yield of roots, tops, and cotyledons (mcgm./pot)}}{\text{Total dry matter yield of roots, tops, and cotyledons (gm./pot)}}$$

Table V. Phosphorus yield (mg./pot) of alfalfa and soybean seedlings 7 days and 16 days after seeding.[1]

Soil Series	7 Days after seeding Root	Top	Coty-ledon	Whole Plant	16 Days after seeding Root	Top	Coty-ledon	Whole Plant
				Alfalfa [2]				
Lualualei	0.29	0.50	0.69	1.48	0.25	0.70	0.39	1.34
Kapaa	0.45	0.28	0.90	1.63	0.60	0.37	0.45	1.42
Sand (no soil)	0.28	0.51	0.71	1.50	0.49	0.65	0.40	1.54
	$D_{0.05}$=0.068				$D_{0.05}$=0.043			
				Soybean				
Lualualei	1.81	2.81	12.19	16.81	3.40	7.70	6.59	17.69
Kapaa	1.49	1.19	11.55	14.23	3.23	4.35	7.46	15.04
Sand (no soil)	1.45	1.54	13.44	16.43	3.11	3.79	6.15	13.05
	$D_{0.05}$=0.88				$D_{0.05}$=0.92			

1/ Mean of replications
2/ Although plants were thinned to uniform population soon after germination, the number of plants per pot varied from 98 to 112 at harvest time. Therefore, yields were adjusted to 100 plants per pot

Analysis of Variance on Phosphorus Yield

Source of Variance	7 days after seeding d.f.	m.s.	16 days after seeding d.f.	m.s.
		Alfalfa		
Replications	2	0.95	2	0.4
Treatment combinations	(8)	-----	(8)	---
Plant Parts	2	460.3**	2	61.0**
Media	2	5.95**	2	9.8**
Plant Part x Media	4	55.5**	4	92.1**
Error	16	0.587	16	0.225
Total	26	-----	26	-----
		Soybean		
Replications	2	0.005	2	0.01
Treatment combinations	(8)	-----	(8)	----
Plant Parts	2	34.22**	2	2.76**
Media	2	0.195**	2	0.55**
Plant Part x Media	4	0.155**	4	0.46**
Error	16	0.0063	16	0.01
Total	26	------	26	-----

It can not necessarily be inferred, therefore, that high phosphorus concentration in these seedlings indicates adequate phosphorus nutrition. It is very probable that phosphorus is immobilized throughout the plant by aluminum and perhaps by iron as well. Fox, De Datta and Wang (unpublished data) demonstrated that young alfalfa grown on unlimed Kapaa soil accumulated about 2800 ppm. aluminum.

The phosphorus yield of alfalfa tops was highest in the plants grown in Lualualei soil, intermediate in sand and lowest in Kapaa soil 16 days after planting (Figure 4). If the phosphorus yield of plants grown in sand represents no uptake and the excess of phosphorus in Lualualei soil-grown plants over plants grown in sand represents phosphorus uptake, then the deficit of phosphorus in plants grown in Kapaa soil suggests phosphorus loss from tops and immobilization of phosphorus in the roots. These differences in phosphorus yield are statistically significant.

The soybean seedlings followed a different trend. Phosphorus yields of tops were largest in Lualualei soil, intermediate in sand and lowest in Kapaa soil 7 days after planting. Sixteen days after planting, phosphorus yields from Kapaa soil were intermediate; sand ranked lowest; and Lualualei soil was again highest (Figure 4). The phosphorus yields of soybean roots, on the other hand, followed a similar trend as those of alfalfa plants. The difference in phosphorus yields were also statistically significant.

Seed phosphorus equivalent to the number of plants harvested per pot of the alfalfa and soybean compared closely with the whole plant phosphorus yields obtained from the plants grown in sand.

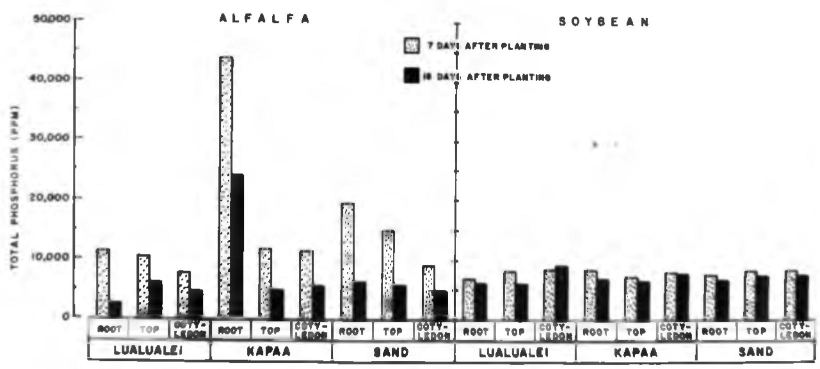

Figure 3. Comparative phosphorus concentration of roots, tops and cotyledons of alfalfa and soybean seedlings, 7 days and 16 days after direct seeding.

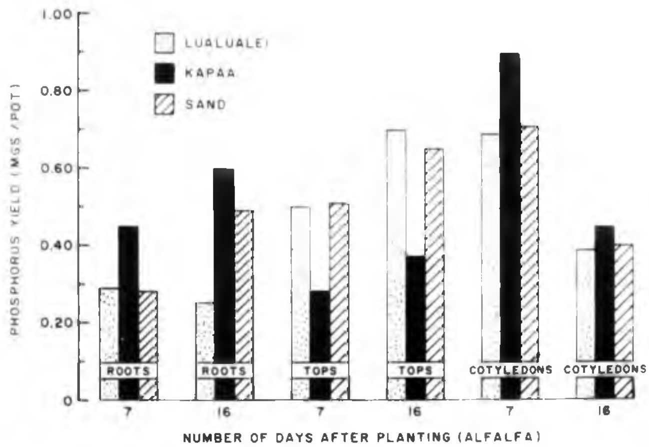

Figure 4. Comparative phosphorus yields of roots, tops, and cotyledons of alfalfa seedlings in relation to plant growth media.

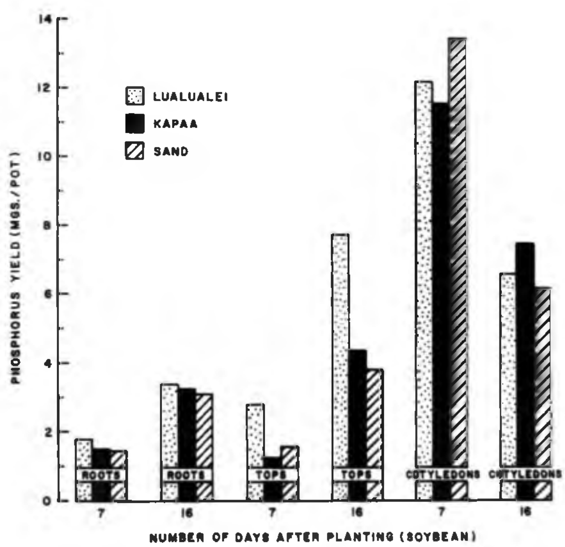

Figure 5. Comparative phosphorus yields of roots, tops, and cotyledons of soybean seedlings in relation to plant growth media.

Plant Species	No. of Seeds Analyzed	Seed Phosphorus (mg.)	Plant Phosphorus Yield in Sand (mg./ pot)
Alfalfa	100	1.27	1.50
Soybean	10	17.63	16.43

One big difference between alfalfa and soybean seedlings was that there was no evidence of phosphorus immobilization in the roots of soybeans. Perhaps soybeans are less sensitive to aluminum toxicity since they have been grown in acid soils where alfalfa fails to grow.

Root pad-soil contact experiment. Results from plant yields from the 5-day root pad-soil contact showed that the yield of roots and tops of Sudan grass was highest in sand, intermediate in Lualualei soil, and lowest in Kapaa soil (Table VI). Phosphorus concentration and phosphorus yield in Sudan grass grown entirely in sand were significantly higher than in plants in contact with Kapaa soil and lower than in plants in contact with the Lualualei soil (Figures 6 and 7.)

The low yield of plants grown in contact with Kapaa soil as compared with that in contact with sand may be explained on the basis of phosphorus status of both plant and medium. Upon soil contact, phosphorus may have moved from the root pad into the newly formed roots developing in a highly phosphate - deficient soil. Assuming that the phosphorus concentration potential of the root at this time was greater than the phosphorus concentration potential of the medium, the tendency would have been for the root to lose phosphorus into the external medium in order to attain equilibrium. This is in agreement with the hypothesis proposed by Dean and Rubins (1945) that the loss of phosphorus from roots to the surrounding clay water system could be explained in terms of equilibrium.

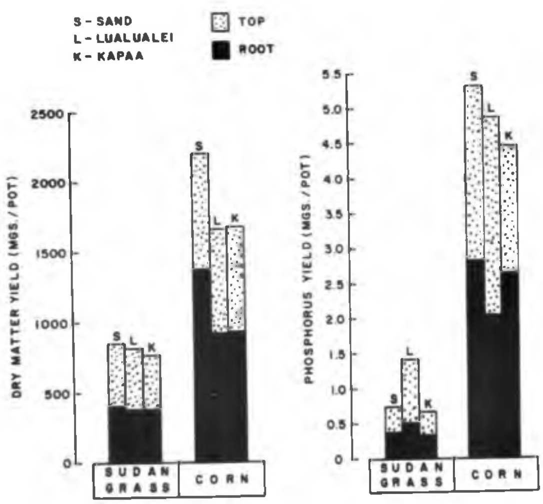

Figure 6. Comparative plant yield and phosphorus yield of Sudan grass and corn seedlings after 5 days of root pad-soil contact.

Apparently, phosphate fixation by the rooting medium tended to shift this equilibrium so that the loss went on until the plants became deficient in phosphorus.

The concentration of phosphorus in Sudan grass roots was lowest in Kapaa soil but highest for corn. The low concentration of phosphorus in the roots of Sudan grass may be a temporary one because of the short root-soil contact (Figure VII).

The concentration of phosphorus in the tops of corn seedlings followed a trend similar to that of Sudan grass, with Lualualei soil having the highest, sand intermediate and Kapaa soil the lowest.

The phosphorus yield of corn, however, was somewhat different from that of Sudan grass. Plants in contact with sand gave the highest yield, Lualualei soil was intermediate, and Kapaa soil remained the lowest. The phosphorus concentration in roots of corn seedings was highest when in contact with Kapaa soil (Figure 7). Expressed in terms of the whole plant, corn, like Sudan grass, loses a significant amount of phosphorus when in contact with Kapaa soil compared with the same plants in contact with sand (Table VI).

The seed phosphorus equivalent to the number of plants harvested per pot of the Sudan grass plants compared well with the whole plant phosphorus yield obtained from Sudan grass plants in contact with sand. The low phosphorus value obtained from corn seeds may be due to poor recovery of the grounded germ in the process of grinding the seed samples.

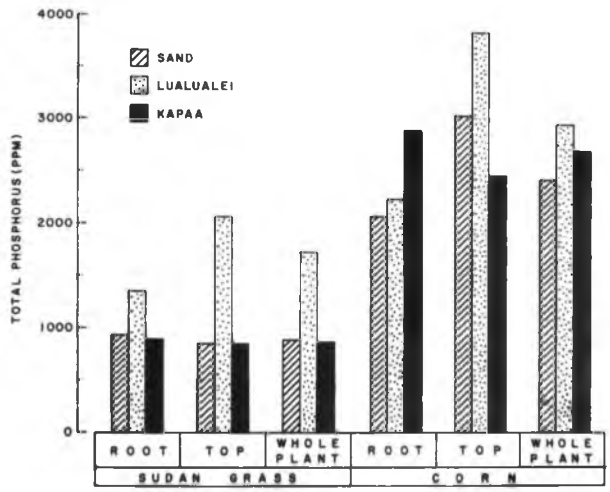

Figure 7. Comparative phosphorus concentration of Sudan grass and corn seedlings in relation to plant growth media after 5 days of root pad-soil contact.

Table VI. Plant yield, phosphorus yield and total phosphorus of Sudan grass and corn seedlings grown in sand for 3 weeks and allowed 5 days root pad-soil contact.1/

Soil Series	Dry matter yield (mg./pot)			Phosphorus Yield (mg./pot)			Phosphorus Concentration (ppm.) 2/		
	Root	Top	Whole Plant	Root	Top	Whole Plant	Root	Top	Whole Plant
				Sudan Grass					
Lualualei	382	436	818	0.51	0.90	1.41	1349	2060	1719
Kappa	385	379	764	0.34	0.32	0.66	896	859	864
Sand	401	445	846	0.37	0.38	0.75	932	859	882
				$D_{0.05}$	= 0.011				
				Corn					
Lualualei	920	742	1662	2.05	2.83	4.88	2227	3827	2940
Kapaa	930	741	1671	2.67	1.82	4.49	2873	2451	2689
Sand	1378	825	2203	2.84	2.49	5.33	2063	3020	2423
				$D_{0.05}$	=1.15				

1/ Mean of 3 replications

2/ Total phosphorus of whole plant (ppm.) =

$$\frac{\text{Total P yield of roots and tops (mcgm./pot)}}{\text{Total dry matter yield of roots and tops (gm./pot)}}$$

Analysis of Variance on Phosphorus Yield

Source of Variance	Sudan Grass d.f.	Sudan Grass m.s.	Corn d.f.	Corn m.s.
Replications	2	0.005	2	0.3868
Treatment Combinations	(5)	-----	(5)	------
Plant Parts	1	0.0729**	1	0.0868(ns)
Media	2	0.25**	2	0.2631(ns)
Plant Parts x Media	2	0.0741**	2	1.0562*
Error	10	0.0016	10	0.1675
Total	17	------	17	------

Plant Species	No. of Seeds Analyzed	Seed Phosphorus (mg.)	Plant Phosphorus Yield in Sand (mg./pot)
Sudan Grass	25	0.80	0.75
Corn	5	3.97	5.33

Undoubtedly, this phosphorus loss will have an adverse effect on the growth and vigor of the plant in the later stages of development.

Experiment II. The uptake of applied fertilizer phosphorus as influenced by time, rates, methods of application and phosphate fixation in soils.

The susceptibility of plant phosphorus to loss from, or immobilization in, roots of seedlings growing in Kapaa soil was demonstrated in Experiment I. The data further indicated that high concentrations of phosphorus are required in the tissues of seedlings for optimum growth. Since phosphorus nutrition is so important in the very early stages of seedling development, a study of the factors influencing efficiency of fertilizer uptake during this period of growth becomes of considerable value. Therefore, Experiment II was undertaken to study some factors which might influence fertilizer phosphorus uptake by corn seedlings during the first three weeks of growth. The factors varied were:

(a) placement of fertilizer phosphorus in the soil (band vs. mixed)

(b) rate of phosphorus application (25 ppm. and 300 ppm.)

(c) nature of the soil (Lualualei soil, low phosphorus fixation vs. Kapaa soil, high phosphorus fixation), and

(d) time of seedling growth (1 week, 2 weeks and 3 weeks).

The phosphorus used was tagged with phosphorus-32 so that plant phosphorus could be recognized as having fertilizer origin or seed-soil origin.

The tops of the corn seedlings were harvested 1, 2, 3 weeks after planting. Plant yields and plant phosphorus were determined. The data obtained are given in Tables VII and VIII.

<u>Yield and Phosphorus Concentration.</u>

External phosphorus supply had very little influence on the growth of corn seedlings during its very early stage of growth. The seed· contained much phosphorus and indications were that the yield of one week old seedlings varied little as a result of fertilizer applications or soil effect. However, it is interesting to note a little trend which indicated that for optimum growth, one week old corn seedlings should contain about 9000 ppm. phosphorus in the leaves - a very high concentration by any standard. A comparison of seedling yields with plant phosphorus is shown in Figure 8. It is interesting to note that per unit of plant phosphorus, seedling yields were generally lower in Kapaa soil. This may have been a specific effect of aluminum such as the effect of aluminum in root development.

With increasing seedling age, soil and fertilizer effects became more evident in seedling yield and composition. At two weeks of age, maximum growth was obtained by plants which contained about 7000 ppm. phosphorus. The data plotted in Figure 8 indicated that plant yield decreased when phosphorus concentration in the plant became excessive. Two treatments were associated with high or excess plant phosphorus: 300 ppm. phosphorus mixed or banded in the Lualualei soil. High percentage phosphorus in the plant was related to low phosphorus fixation in Lualualei soil; and, of course, the generous rate of phosphorus applied to the soil.

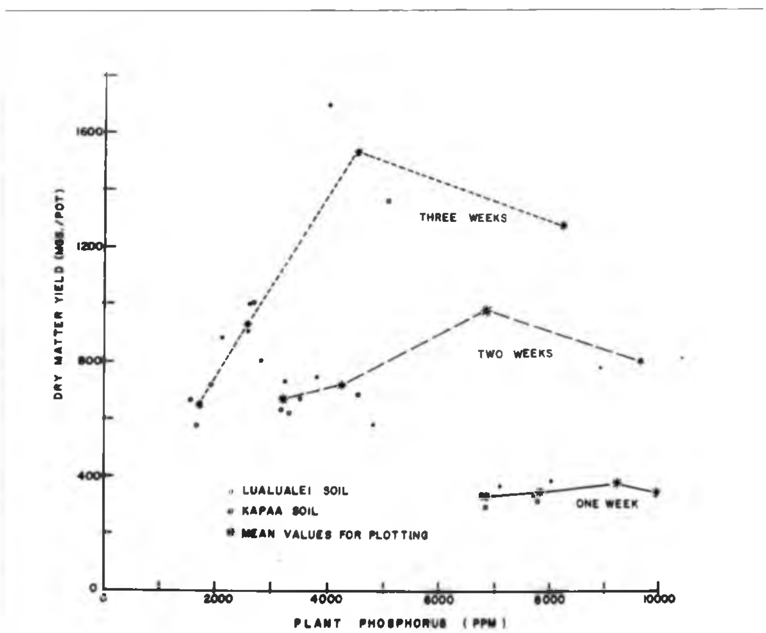

Figure 8. Influence of plant phosphorus on the dry matter yield of corn seedlings at 1 week, 2 weeks and 3 weeks of growth.

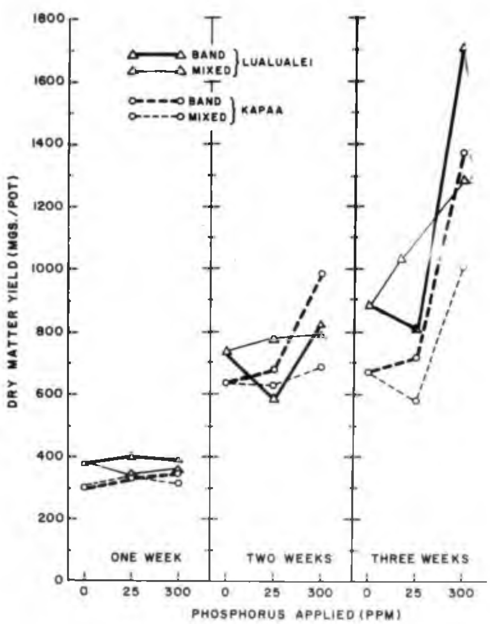

Figure 9. Influence of time, rates, methods of phosphorus application and phosphate fixation on the dry matter yields of corn seedlings grown in Lualualei and Kapaa soils.

Plant yields plotted against plant phosphorus in 3-week old corn seedling gave trends which corresponded with the pattern clearly evident at two weeks. However, the data plotted in Figure 8 indicated that at this advanced age, optimum phosphorus concentration in the leaves was about 4000 ppm. phosphorus.

Since excess phosphorus uptake by the corn seedlings was evident in some instances, it would not be wise to interpret the efficiency of fertilizer placement on the basis of plant yield. Phosphorus uptake, either as total phosphorus or phosphorus derived from the fertilizer, will be a much more meaningful criterion.

Total Plant Phosphorus and Phosphorus Yield.

Total phosphorus concentration in the corn seedlings decreased from the first week to the third week of growth, regardless of rate and method of phosphorus application or soil (Figure 10). This decrease in phosphorus concentration with time may be mainly a dilution effect as a result of growth.

Total phosphorus yield in corn seedlings grown in Lualualei and Kapaa soils was examined statistically. A highly significant interaction among the factors of time of growth, method of application and rate of phosphorus application is indicated (Tables VII and VIII). In general, throughout the first and second week of growth, the 300 ppm. fertilizer phosphorus mixed with the Lualualei soil gave a higher phosphorus yield than the band application (Figure 11). However, after the third week of growth, phosphorus yield was higher when fertilizer phosphorus (300 ppm.) was mixed with Lualualei soil than when the same amount was band applied. This indicated that in spite of root development at the third week of growth, activity of absorption did not

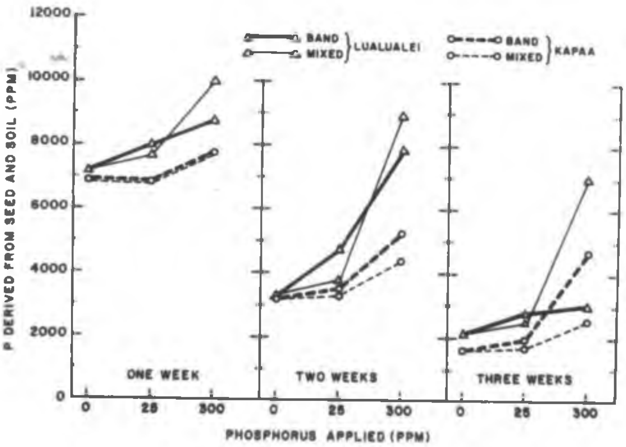

Figure 10. Influence of time, rates, methods of phosphorus application and phosphorus fixation on the total phosphorus concentration of corn seedlings grown in Lualualei and Kapaa soils.

Table VII. Plant yield, phosphorus concentration and phosphorus yield of corn seedlings as affected by time, rates, methods of phosphorus application and phosphate fixation in Lualualei soil

P Rate (ppm.)	P Placement	Yield (mg./pot)	Total P (ppm.)	P Yields (mg./pot)	P From Fert. (ppm.)	P Yield From Fert. (mg./pot)	P From Fert. (% of total)	P From Seed. & Soil (ppm.)
				1 Week Old				
0	----	374	7109	2.65	----	-----	----	7109
25	Band	393	8006	3.14	83	0.033	1.04	7923
	Mixed	340	7700	2.67	57	0.019	0.73	7643
300	Band	385	9214	3.36	503	0.193	5.45	8711
	Mixed	356	9969	3.56	676	0.240	6.74	9293
				2 Weeks Old				
0	-----	733	3218	2.33	----	-----	----	3218
25	Band	584	4833	2.82	110	0.065	2.28	4723
	Mixed	775	3800	2.94	54	0.042	1.39	3746
300	Band	790	8902	7.03	1121	0.885	12.59	7781
	Mixed	823	10405	8.56	1519	1.250	14.60	8886
				3 Weeks Old				
0	-----	886	2086	1.85	----	-----	-----	2086
25	Band	806	2847	2.29	121	0.097	4.26	2726
	Mixed	1032	2623	2.70	101	0.106	3.87	2522
300	Band	1706	3989	6.80	1012	1.725	25.38	2977
	Mixed	1289	8020	10.34	1074	1.384	13.39	6946
			$D_{0.05}$	=1.11		=0.10	=10.39	

Analysis of Variance

Source of Variance	Total P Yield d.f.	Total P Yield m.s.	P Derived From Fert. d.f.	P Derived From Fert. m.s.	P Derived From Fert. (% of total) d.f.	P Derived From Fert. (% of total) m.s.
Replications	2	0.250	2	0.1508	2	0.105
Treatment Combinations	(17)		(11)		(11)	
Time (T)	2	10.35**	2	152.89**	2	203.54**
Methods (M)	1	4.75**	1	4.55(ns)	1	26.39(ns)
Rates (R)	2	101.39**	1	706.49**	1	1042.43**
T x M	2	2.23**	2	8.54**	2	45.05*
T x R	4	18.20**	2	12.31**	2	78.95**
M x R	2	4.57**	1	0.23(ns)	1	12.70(ns)
T x M x R	4	1.16**	2	10.24**	2	48.28*
Error	34	0.139	22	0.114	22	12.29
Total	53	-----	35	-----	35	-----

Table VIII. Plant yield, phosphorus concentration and phosphorus yield of corn seedlings as affected by time, rates, methods of phosphorus application and phosphate fixation in Kapaa soil

P Rate (ppm.)	P Place-ment	Yield (mg./pot)	Total P Yield	P Yields (mg./pot)	P From Fert. (ppm.)	P Yield From Fert. (mg./pot)	P From Fert. (% of total)	P From Seed & Soil (ppm.)
			1 Week Old					
0	-----	300	6818	2.04	---	-----	----	6813
25	Band	333	6752	2.25	6	0.002	0.08	6746
	Mixed	339	6748	2.29	3	0.001	0.04	6745
300	Band	357	7841	2.79	146	0.053	1.86	7695
	Mixed	322	7764	2.50	93	0.030	1.20	7671
			2 Weeks Old					
0	-----	635	3173	1.91	---	-----	----	3173
25	Band	676	3502	2.37	16	0.011	0.45	3486
	Mixed	624	3295	2.06	7	0.005	0.22	3288
300	Band	988	6825	6.74	616	0.609	9.03	6209
	Mixed	688	4532	3.27	176	0.122	3.89	4356
			3 Weeks Old					
0	-----	673	1544	1.04	---	------	----	1544
25	Band	718	1902	1.36	11	0.008	0.59	1891
	Mixed	581	1660	0.96	7	0.005	0.44	1653
300	Band	1372	5053	6.93	430	0.589	8.50	4623
	Mixed	1009	2663	2.58	179	0.179	6.98	2484
		$D_{0.05}$		=0.72		=0.074	=1.339	

Analysis of Variance

Source of Variance	Total P Yield d.f.	Total P Yield m.s.	P Derived From Fert. d.f.	P Derived From Fert. m.s.	P Derived From Fert. (% of total) d.f.	P Derived From Fert. (% of total) m.s.
Replications	2	0.005	2	0.006	2	0.05
Treatment Combinations	(17)		(11)		(11)	
Time (T)	2	3.13**	2	11.54**	2	36.89**
Methods (M)	1	12.74**	1	21.59**	1	15.05**
Rates (R)	2	33.26**	1	60.11**	1	219.53**
T x M	2	2.85**	2	4.76**	2	4.56**
T x R	4	2.01**	2	10.78**	2	28.05**
M x R	2	610.19**	1	0.64**	1	11.91**
T x M x R	4	5.57**	2	14.57**	2	3.94**
Error	34	0.058	22	0.062	22	0.203
Total	53	-----	35	-----	35	-----

shift away from the concentrated band layer of phosphorus supply. The corn seedlings took up more phosphorus than what was actually needed. Fixation of the fertilizer phosphorus mixed with soil could also be a factor.

Band applied phosphorus in Kapaa soil gave higher total phosphorus yield than did fertilizer mixed with the soil (Figure 11). This was for the three period of growth and both the 25 and 300 ppm. rates of application. Kapaa soil has a very high phosphorus fixing capacity, as was demonstrated by laboratory studies. It is probable that more of the band applied phosphorus remained soluble thus in a more available form than when fertilizer was diluted by mixing with soil.

Percentage of Phosphorus Derived from Fertilizer.

Percentage of phosphorus fertilizer of corn seedlings after three weeks of growth was higher when the fertilizer phosphorus was band applied to Lualualei soil. When 300 ppm. of phosphorus was mixed with the soil, phosphorus recovery by the plant as measured at the end of 1 week and after 2 weeks was higher than when the fertilizer phosphorus was band applied. When the seedlings were sampled at the end of three weeks, a reverse relationship was obtained; i.e., band applied fertilizer more effectively supplied phosphorus than did fertilizer mixed with the soil (Figure 12). A possible explanation for these data follows:

A high concentration of fertilizer phosphorus in the band created a "superabundant" condition with respect to phosphorus uptake by the root. In other words, the rooting medium initially supplied phosphorus greatly in excess of what the plant root could take up effectively.

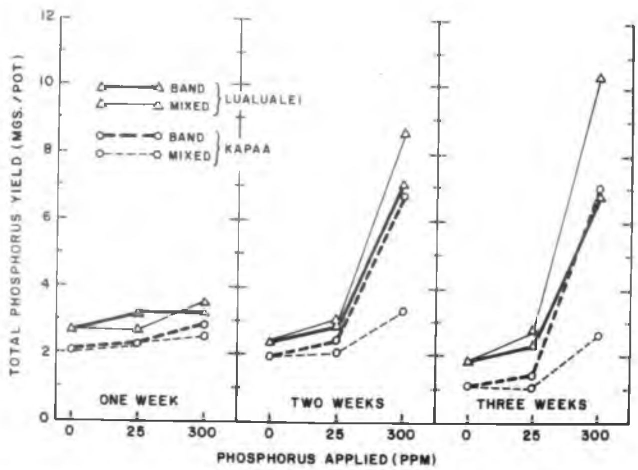

Figure 11. Influence of time, rates, methods of phosphorus application and phosphate fixation on the total phosphorus yield of corn seedlings grown in Lualualei and Kapaa soils.

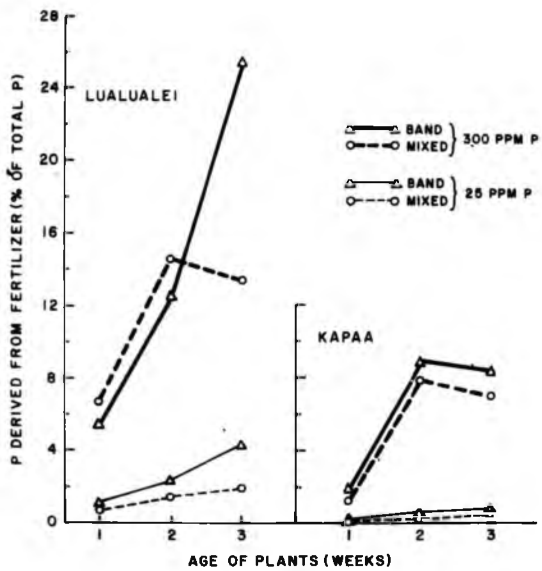

Figure 12. Influence of time, rates, methods of phosphorus application and phosphate fixation on the fertilizer phosphorus uptake of corn seedlings grown in Lualualei and Kapaa soils.

Phosphorus uptake per unit root per unit phosphorus was low. This condition did not exist or at least was less critical during the same time of growth when the fertilizer phosphorus (300 ppm.) was mixed with soil. By mixing the fertilizer with the soil, root-fertilized soil contact was greater than when fertilizer was band applied, and phosphorus concentration was reduced to a point of greater efficiency of uptake per unit phosphorus. The net effect was increased phosphorus uptake by the plant, indicating that in soils of low phosphate fixing capacity, benefit from extensive root-fertilized soil contact may over-ride phosphorus fixation.

The superiority of band application over that of mixing in Lualualei soil after the third week of growth suggested that the volume of the soil in the fertilized band increased as a result of movement of excess phosphorus from the "superabundant" zone. The data suggested further that for soil of low phosphate fixing capacity, a larger volume of fertilized soil for root exploration was formed by the movement of excess phosphorus. It should be noted, however, that the kind of crop and its root distribution pattern are important in determining the efficiency of a particular fertilizer placement pattern. The studies reported by Hall (1951) indicated that corn absorbs heavily from the top 3 - inch layer of the soil during the first few weeks; and Nelson et al. (1949) reported a rapid decline in the uptake of corn after the fourth week of growth.

In Kapaa soil where phosphorus immobilization is essentially complete, fertilizer phosphorus placement by band application was consistently superior to mixing for seedling development regardless of the amount of fertilizer applied during the short

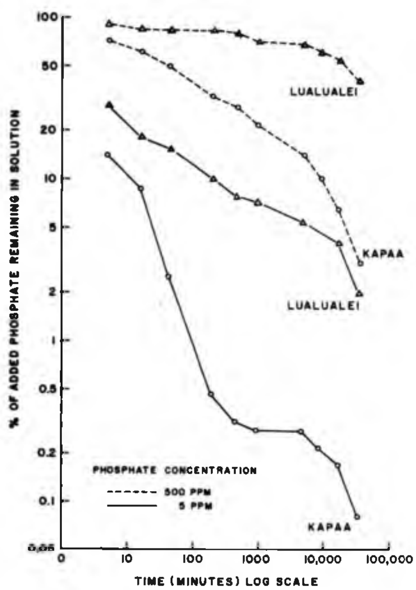

Figure 13. Immobilization of phosphorus by 2 Hawaiian soils (Yaptenco *et al.*, 1963)

period of time these plants grew (Figure 12). In studies reported by Yaptenco et al. (1963), it was estimated that in Kapaa soil, only 7% of the added 500 ppm. phosphate remained in solution after 12 days of soil-phosphate solution contact (Figure 13).

The general decrease of seed and soil phosphorus concentration in corn seedlings from the first week to the third week of growth is shown in Figure 14. These results indicated a dilution effect as a result of growth.

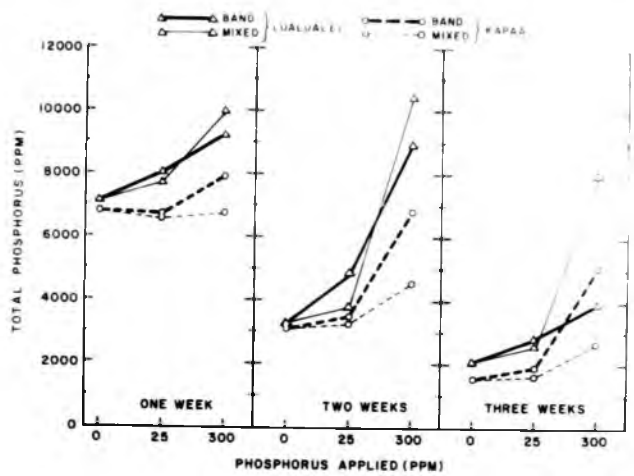

Figure 14. Influence of time, rates, methods of phosphorus application and phosphate fixation on the seed and soil phosphorus concentration of corn seedlings grown in Lualualei and Kapaa soils.

SUMMARY AND CONCLUSIONS

The influence of phosphorus fixation by soils on the phosphorus nutrition of various seedlings was studied. Two Hawaiian surface soils, Dark Magnesium Clay (Lualualei series) and Aluminous Ferruginous Latosol (Kapaa series) were used.

Two techniques, direct seeding and root pad-soil contact, were employed to investigate possible losses of phosphorus from seedling roots in relation to phosphate fixation by the two soils. Alfalfa, soybean, Sudan grass and corn were used as experimental plants.

The influence of time of growth, method of fertilizer phosphorus application, and rate of phosphorus application on the efficiency of fertilizer phosphorus uptake by corn seedlings in Lualualei and Kapaa soils were determined. Phosphorus-32 was used to identify the plant phosphorus of fertilizer origin.

From a study of the data obtained in this investigation, the following conclusions seem justified:

1. The experimental plants (alfalfa, soybean, Sudan grass and corn) varied in their response to phosphorus fixation in Lualualei and Kapaa soils.

2. The immobilization of phosphorus in the roots of alfalfa and Sudan grass seedlings was associated with the aluminum and/or iron status of the rooting medium.

3. Seedling roots accumulated seed phosphorus at the expense of the phosphorus in the tops. The phosphorus loss from tops and the immobilization of phosphorus in the roots adversely affected growth.

4. For maximum growth, corn seedlings should have approximately 9000 ppm. phosphorus in the dry matter at 1 week, 7000 ppm. at 2 weeks and 4000 ppm. after 3 weeks of growth.

5. For supplying phosphorus to corn up to 3 weeks of growth, the band application method was definitely more effective in soils with a phosphorus fixation problem. However, in soils where phosphate fixation is not a problem, mixing the fertilizer with the soil was more effective. This is not to say that this will prove to be the most effective way of fertilizing corn for more extended period of growth.

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